Ingeniería y Competitividad
Vol 27 (2) 2025 doi: 10.25100/iyc.v27i2.14813

Vol 27 (2)

ISSN
0123-3033
e- 2027-8284

Original Article

Electricity generation with biogas from sugarcane vinasse in Colombia

Generación eléctrica con biogás de vinaza de caña en Colombia

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How to cite?

Infante-Cuan JE, Martínez-Campo SD, Sierra-Carrillo MM, Rozo-Martínez LR, Muñoz P. Electricity generation with biogas from sugarcane vinasse in Colombia. Ingeniería y Competitividad, 2025, 27(2)e-20214813

https://doi.org/10.25100/iyc.v27i2.14813

Received: 03/19/25
Reviewed: 04/9/25
Accepted: 04/28/25
Online: 05/2/25

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Spanish version

Abstract

Introduction: The consumption of bioenergy has increased in recent years, contributing to the reduction of greenhouse gas (GHG) emissions. In particular, sugarcane waste has been evaluated in several studies as a potential source of renewable energy. The sugar industry primarily produces sugar and ethanol, and for each liter of ethanol produced, between 10 and 15 liters of vinasse are generated. This residue is highly polluting and, although it is traditionally used for fertigation or disposed of, it holds significant potential for biogas production.
Objectives:The main objective of this study was to assess the electricity generation potential from vinasse produced in ethanol plants in Colombia and calculate the CO2 emissions avoided by substituting local electricity use with this renewable energy source.
Materials and Methods: Four different scenarios were evaluated based on the percentage of sugarcane juice used for ethanol production. For each scenario, the electricity generation potential from biogas produced by vinasse biodigestion was calculated. Additionally, the CO2 emissions avoided were estimated by comparing the use of vinasse-based electricity with local conventional electricity sources.
Results: The results from the different scenarios show that the electricity generation potential ranges between 249,840.36 MWh/year and 437,156.37 MWh/year, depending on the percentage of sugarcane juice used for ethanol production. CO2 emissions avoided ranged from 31,475.26 to 55,081.70 tons of CO2/year. These results indicate that electricity generation from vinasse has a significant impact on reducing greenhouse gas emissions compared to local conventional electricity.
Conclusions: The valorization of sugarcane vinasse for electricity generation represents a significant step forward in the production of clean electricity in the sugar sector. The results show that this approach not only has high potential for renewable energy generation but also contributes significantly to reducing CO2 emissions, enhancing the sustainability of the sector.

Keywords: Methane, biodigester, energy, sustainable production, renewable source, Sustainability.

Resumen

Introducción: El consumo de bioenergía ha experimentado un aumento en los últimos años, lo que ha contribuido a la reducción de las emisiones de gases de efecto invernadero (GEI). En particular, los residuos de caña de azúcar han sido evaluados en diversos estudios como una fuente potencial de energía renovable. La industria azucarera genera principalmente azúcar y etanol, y por cada litro de etanol producido, se generan entre 10 y 15 litros de vinaza. Este residuo es altamente contaminante y, aunque tradicionalmente se utiliza en fertirrigación o se desecha, presenta un alto potencial para la producción de biogás.
Objetivos: El objetivo principal de este trabajo fue evaluar el potencial de generación de electricidad a partir de la vinaza producida en plantas de etanol en Colombia, así como calcular las emisiones de CO2 evitadas al sustituir el uso de electricidad local mediante esta fuente de energía renovable.
Materiales y Métodos: Se evaluaron cuatro escenarios distintos en función del porcentaje de jugo de caña utilizado para la producción de etanol. Para cada escenario, se calculó el potencial de generación eléctrica a partir del biogás producido por la biodigestión de vinaza. Además, se estimaron las emisiones de CO2 evitadas mediante la comparación con la electricidad proveniente de fuentes locales convencionales.
Resultados: Los resultados obtenidos en los diferentes escenarios muestran que el potencial de generación eléctrica varía entre 249.840,36 MWh/año y 437.156,37 MWh/año, dependiendo del porcentaje de jugo de caña utilizado para la producción de etanol. Las emisiones de CO2 evitadas fluctuaron entre 31.475,26 y 55.081,70 toneladas de CO2/año. Estos resultados indican que la generación de electricidad a partir de la vinaza tiene un impacto significativo en la reducción de las emisiones de gases de efecto invernadero en comparación con la electricidad local convencional.
Conclusiones: La valorización de la vinaza de caña de azúcar para la generación de electricidad representa un avance significativo hacia la producción de energía eléctrica limpia en el sector azucarero. Los resultados muestran que este enfoque no solo tiene un alto potencial para la generación de energía renovable, sino que también contribuye de manera importante a la reducción de las emisiones de CO2, lo que mejora la sostenibilidad del sector.

Palabras clave: Metano, biodigestor, energía, producción sostenible, fuente renovable, sostenibilidad

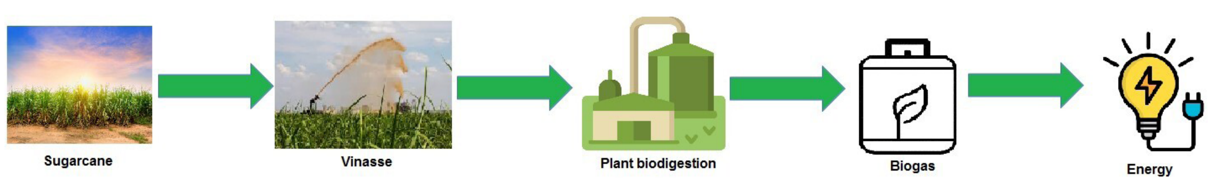
Contribution to the literature

The study was conducted to evaluate the potential for electricity generation from biogas produced through the anaerobic biodigestion of vinasse, a highly polluting byproduct generated in the production of bioethanol from sugarcane in Colombia. The main motivation is twofold: (1) to find a sustainable alternative for the treatment of vinasse, whose improper disposal can cause serious environmental impacts, such as groundwater contamination and soil desertification; and (2) to contribute to the country's energy transition by recovering agro-industrial waste, in line with the principles of the circular bioeconomy and Colombia's climate commitments.

The most relevant results include:
Four scenarios were analyzed with different percentages of sugarcane juice used for ethanol production (40%, 50%, 60%, and 70%). It was estimated that annual electricity generation could range between 249,840 MWh/year (scenario 1) and 437,156 MWh/year (scenario 4), representing between 0.31% and 0.54% of Colombia's national electricity consumption in 2022. Avoided CO□ emissions were estimated to range between 31,475 and 55,081 tons per year, equivalent to 0.018% and 0.031% of the national emissions reduction target for 2030.

These results contribute to the following:
This work provides technical evidence to support public policies for waste recovery, energy planning, and climate change mitigation strategies. It also provides a replicable methodological basis for other countries or regions with significant sugarcane production. Finally, it promotes the transition to a circular bioeconomy, where industrial waste is transformed into energy resources, reducing both environmental impacts and dependence on fossil fuels.

Graphical Abstract



doi: 10.25100/iyc.v27i2.14813

Introduction

Today's society is facing problems such as the generation and accumulation of waste, climate change and the depletion of fossil fuels, which is why a concept called the circular bioeconomy is being developed and implemented (1). This concept is defined as the valorisation of by-products for the production of value-added products from biomass with a reduction in waste generation (2). Today, among the many renewable energy sources, sugarcane is one of the most important crops in the world and an important contributor to energy diversification and sustainable development (3).

This crop has spread throughout the world, particularly in tropical and subtropical countries (4). It is estimated that sugarcane production will be around 2.1 billion tonnes by 2025 (5). In Colombia, between 2010 and 2019, the area planted with sugarcane exceeded 200,000 hectares, with a maximum of 243,232 hectares in 2017 and a minimum of 241,205 hectares in 2019 (6). In recent years, the sugarcane industry in Colombia has moved towards the valorisation of industrial waste (7). For example, in 2022, the Colombian sugarcane agroindustry had a production of: 23 million tonnes of sugarcane, 2.09 million tonnes of sugar, 1,745 GWh of energy produced from sugarcane bagasse, and 347 million litres of bioethanol from sugarcane (8). From a circular bioeconomy perspective, the generation of by-products and waste from sugarcane processing has raised some environmental concerns (9), due to the fact that sugarcane processing generates numerous wastes, including bagasse and vinasse (5,10).

Bioethanol production generates a residue called vinasse. This residue is produced in the bioethanol fermentation-distillation process at a rate of between 10-15 L per litre of bioethanol produced (11–13). Its main characteristics are its dark brown colour (14), it is highly polluting due to its low pH (around 4), high biochemical oxygen demand (BOD) (45,000 to 60,000 mg/L) (15), high chemical oxygen demand (COD) (71,400 to 134,400 mg/L) (16), high potassium content (3,600 mg/L) and significant amounts of nitrogen, phosphorus and micronutrients (17,18). Current practices for vinasse management include: composting, fertigation, energy production, microalgae culture medium and raw material for livestock and poultry production (14).

Among them, the most common is fertigation, which consists of the direct application of untreated vinasse in nature to the soil (11).This technique is widely applied due to its low investment and maintenance costs compared to other alternatives (19). However, the disposal of vinasse in nature can lead to groundwater contamination and soil desertification due to high COD contents (18,20). Therefore, the implementation of technologies for the use, treatment and proper disposal of vinasse is of great importance, with the aim of improving its use and/or using it to obtain other products of economic interest (13,21,22).

Alternatives are currently being evaluated to manage and even valorize this by-product (23). An interesting alternative to the treatment of vinasse is anaerobic digestion, which allows recovering part of its energy content thanks to the production of biogas (24). This biological process, well documented in the literature, degrades a high concentration of organic matter in the absence of oxygen, through four main stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis (25,26). The anaerobic digestion process for biogas production using sugarcane vinasse as feedstock

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has the advantage of degrading a high concentration of organic matter, moreover, it is a well-documented and promising approach for bioeconomy and bioenergy due to its wide variety of applications (27,28). The use of vinasse as a substrate in the anaerobic digestion process has been extensively studied (16,29,30). The main end products obtained from anaerobic digestion are biogas and fertilizers, which can be used for energy recovery and soil amendment, respectively (1).

Biogas consists mainly of methane (CH_4) (45-70%), carbon dioxide (CO_2) (25-55%) and traces of other compounds (nitrogen, oxygen, hydrogen, sulphur and water vapour) (31). It can be used as an alternative fuel, replacing bagasse as an energy source in boilers for electricity production and, if improved (methane content >97%, v/v), it can be used as a fuel in vehicles or injected into natural gas networks (32–34).

Biogas production efficiency depends on factors such as temperature, pH, carbon-to-nitrogen (C/N) ratio, and the presence of inhibitors such as sulfates or heavy metals (35). Two temperature ranges are mainly used: mesophilic (35–40 °C) and thermophilic (50–60 °C). Although thermophilic conditions allow higher biogas yields, they require higher energy inputs (36). Maintaining optimal conditions is key to avoid microbial inhibition and maximize biogas production (37).

The implementation of anaerobic digestion to valorize vinasse also contributes significantly to the reduction of greenhouse gas (GHG) emissions. The use of biogas avoids methane emissions from the natural anaerobic decomposition of vinasse and replaces fossil fuel-based energy sources (38). Furthermore, the integration of anaerobic digestion systems in the sugar agroindustry can strengthen its energy self-sufficiency, reduce costs, and generate additional income through the commercialization of surplus electricity or biomethane (39). These actions are aligned with national and international sustainability policies, improving the competitiveness of the sector (40).

Based on the above, the objective of this study was to determine the potential for electricity generation from biogas from the biodigestion of vinasse produced during the distillation of bioethanol in the sugar energy sector in Colombia, and to calculate the amount of emissions avoided by not using local electricity. Therefore, the evaluation of electricity generation from biogas derived from the biodigestion of sugarcane vinasse could be a technological route to strengthen the concept of the circular bioeconomy.

Material and methods

Primary sugarcane production in Colombia is located in 30 municipalities in Valle del Cauca, 9 in Cauca, 5 in Caldas and another 5 in Risaralda, as well as 1 in Quindío. Thanks to the region's privileged climate, and contrary to what happens in the rest of the world (with the exception of Hawaii and northern Peru), sugarcane can be planted and harvested during all months of the year (8). Agroindustrial sugar production is carried out in 12 mills with an installed milling capacity of 94,000 tons per day, where 6 of the 12 mills also produce bioethanol.

doi: 10.25100/iyc.v27i2.14813

Table 1. Installed milling capacity for the different mills

Distillery	Installed milling capacity (t/d)
Riopaila Castilla*	17,600
Incauca*	17,000
Manuelita*	11,500
Providencia*	10,000
Mayagüez*	10,000
Central Castilla	8,000
La Cabaña	5,200
Risaralda*	5,000
Pichichí	4,400
Carmelita	2,500
San Carlos	2,000
María Luisa	800
Total	94,000

* Produce bioethanol

One of the most important features of the sugar-energy sector is the possibility to flexibly produce sugar or bioethanol in one and the same industrial plant. Depending on market demands, the production of sugar and bioethanol has an impact on the production of vinasse and consequently on the volume of biogas resulting from its biodigestion.

During sugar cane processing, it is necessary to define the quantity of each product to be produced. This definition takes place immediately after the extraction of the sugar cane juice, with the determination of how much of the juice will be used for sugar production and how much will be used for bioethanol production, i.e. at this point the plant's production mix is defined. The production mix of a plant becomes a direct interfering factor in the potential for electricity production from the biogas extracted from the vinasse (41).

A literature review was carried out to develop this work, including technical articles, books, websites and industry reports. A sequential estimation spreadsheet using Excel software was used to develop the simulations. The methodology used to calculate the potential for electricity generation from biogas followed the same method used by (42,43). The development of the calculations was based on the installed milling capacity of mills in Colombia producing bioethanol. In developing the simulations, four scenarios of electricity production from biogas derived from the biodigestion of sugarcane vinasse in Colombia were considered:

a) Electricity production potential when 40% of cane juice is used for ethanol production (Scenario 1). b) Electricity production potential when 50% of the cane juice is used for ethanol production (Scenario 2). c) Electricity production potential when 60% of the cane juice is used for ethanol production (Scenario 3). d) Electricity production potential when 70% of the cane juice is used for ethanol production (Scenario 4).

The selection of these percentages responds to several technical and strategic reasons. First, these values allow for modeling different levels of industrialization in the sugar sector, reflecting both current practices and potential expansions of ethanol production capacity in Colombia.

doi: 10.25100/iyc.v27i2.14813

Furthermore, the study seeks to analyze how increasing the proportion of sugarcane juice used for ethanol would directly impact the amount of vinasse available for biodigestion and, consequently, the potential for generating electricity and reducing greenhouse gas emissions. This phased approach allows for assessing the progressive nature of energy and environmental benefits, providing valuable input for public policy formulation, energy planning, and the promotion of agroindustrial waste utilization technologies as strategies for meeting national climate commitments.

Electric power generation potential

The volume of ethanol production was calculated from equation 1.

$$VED = (TD * Mix) * TEP \quad (1)$$

Where:

VED = Ethanol production volume m^3/d; TD = sugar cane milling capacity t/d; Mix = percentage of ethanol to be produced and TEP = production rate of ethanol produced (litres) per tonne of sugar cane.

The volume of vinasse produced was calculated from equation 2.

$$VVG = VED * TPV \quad (2)$$

Where:

VVG = Volume of vinasse produced in m^3/d and TPV = production rate in m^3 of vinasse per m^3 of ethanol produced.

The content of organic load in the vinasse is given by equation 3.

$$CO = VVG * COD \quad (3)$$

Where:

CO = organic load (kg COD/d) and COD = chemical oxygen demand in mg/l.

Biogas production from anaerobic biodigestion using an UASB (Upflow Anaerobic Sludge Blanket) biodigester is given by equation 4.

$$PB = CO * E * F \quad (4)$$

Where:

PB = Biogas production in Nm^3/d; E = COD removal efficiency of the process and F = biogas conversion factor per COD removed;

The amount of energy from biogas can be calculated from equation 5.

$$GEB = PB * LCBP \quad (5)$$

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Where:

GEB = amount of biogas energy in kcal/d; and LCBP = lower calorific value of biogas in kcal/Nm³.

It is important to note that the calculations of biogas production, organic load and biogas energy quantity are referenced to daily production. For the development of this study it was assumed that the plant operated 365 days a year. The three most commonly used ways of using vinasse biogas for energy are: a) thermal energy generation; b) automotive use; and c) electricity generation. For this study, the objective is to identify the potential for electricity generation from vinasse biogas, so the other forms of utilisation of this energy source were not analysed.

The amount of electrical energy that will be produced by the combustion of biogas depends on the type of turbine/equipment set to be used in the process and is given by equation 6.

$$PEEB = GEB * E1 \quad (6)$$

Where:

PEEB = amount of electrical energy generated from biogas combustion in kcal/d and E1 = efficiency of the gas turbine.

GHG emissions avoided

The avoided greenhouse gas (GHG) emissions indicate the potential reduction of GHG emissions from the production facility, taking into account methane production to estimate the reduction of GHG emissions. The avoided GHG emissions from electricity were estimated using equation 7 (44).

$$A_{GHG} = PEEB * EF \quad (7)$$

Where:

AGHG = avoided emissions and EF: emission factor in tonnes of CO_2/MWh for Colombian electricity generation in 2021.

Results and discussion

Due to the difficulty in obtaining some of the data necessary to perform the calculations based on the nature and process of vinasse biogas production, it was necessary to pre-define some parameters. The main variables used to estimate the amount of ethanol produced, the amount of vinasse produced, the amount of biogas produced and the amount of electrical energy produced by the combustion of biogas are found in table 2.

doi: 10.25100/iyc.v27i2.14813

Table 2. Parameters used for the study

Variable	Value
Rate of ethanol production	0.08 L/tonne of sugarcane (41).
Vinasse production rate	11.5 m^3 of vinasse/m^3 of ethanol (41).
Chemical oxygen demand	40,000 mg/L (45).
Process COD removal efficiency	70%
Biogas conversion factor per COD removed	0.45 m^3/kg
Lower calorific value of biogas	5,100 kcal/Nm^3 (45).
Efficiency of gas turbines	35% (46).
Conversion factor	0.001163 kWh/kcal.
Emission factor	0.126 kg CO_2/kWh (47).

Using equations 1 - 6 and the information in Table 1, it was possible to calculate the variables needed to estimate the amount of electrical energy produced by the combustion of biogas. Tables 3 - 6 show the results of the calculation of the variables used at this stage of the research for the 4 scenarios studied.

Table 3. Results for Scenario 1

Distillery	VED (m^3/d)	VVG (m^3/d)	CO (kg COD/d)	PB (Nm^3/d)	GEB (kcal/d)	PEEB (MWh/d)
Riopaila Castilla	563.2	6,470.8	259,072	81,607.68	416,199,168	169.41
Incauca	544	6,256	250,240	78,825,6	402,010,560	163.64
Manuelita	368	4,232	169,280	53,323.2	271,948,320	110.70
Providencia	320	3,680	147,200	46,368	236,476,800	96.26
Mayagüez	320	3,680	147,200	46,368	236,476,800	96.26
Risaralda	160	1,840	73,600	23,184	118,238,400	48.13

Table 4. Results for Scenario 2

Distillery	VED (m^3/d)	VVG (m^3/d)	CO (kg COD/d)	PB (Nm^3/d)	GEB (kcal/d)	PEEB (MWh/d)
Riopaila Castilla	704	8,096	323,840	102,009.6	520,428,960	211.77
Incauca	680	7,820	312,800	98,532	502,513,200	204.55
Manuelita	460	5,290	211,600	66,654	339,935,400	138.37
Providencia	400	4,600	184,000	57,960	295,596,000	120.32
Mayagüez	400	4,600	184,000	57,960	295,596,000	120.32
Risaralda	200	2,300	92,000	28,980	147,798,000	60.16

The electricity generation potential for Scenario 1 was 249,8403.64 MWh/year, Scenario 2 can produce 312,254.55 MWh/year, which is 25% higher compared to Scenario 1. Scenario 3 can produce 374,705.46 MWh/year, which is 20% and 50% higher than Scenario 2 and Scenario 1 respectively. Finally, scenario 4 can produce 437,156.37 MWh/year, which is 75%, 40% and 16.7% higher than scenarios 1, 2 and 3 respectively. Figure 1 shows the electricity generation potential for the different scenarios studied.

doi: 10.25100/iyc.v27i2.14813

Table 5. Results for Scenario 3

Distillery	VED (m³/d)	VVG (m³/d)	CO (kg COD/d)	PB (Nm³/d)	GEB (kcal/d)	PEEB (MWh/d)
Riopaila Castilla	844.80	9,715.20	388,608	122,411.52	624,298,752	254.12
Incauca	816	9,384	375,360	118,298.40	603,015,840	245.46
Manuelita	552	6,384	253,920	79,984.80	407,922,480	166.04
Providencia	480	5,520	220,800	69,552	354,715,200	144.39
Mayagüez	480	5,520	220,800	69,552	354,715,200	144.39
Risaralda	240	2,760	110,400	34,776	177,357,600	72.19

Table 6. Results for Scenario 4

Distillery	VED (m³/d)	VVG (m³/d)	CO (kg COD/d)	PB (Nm³/d)	GEB (kcal/d)	PEEB (MWh/d)
Riopaila Castilla	985.6	11,344.4	453,376	142,813.44	728,348,544	296.47
Incauca	952	10,948	437,920	137,944.8	703,518,480	286,37
Manuelita	644	7,406	296,240	93,315.6	475,909,560	193,72
Providencia	560	6,440	257,600	81,144	413,834,400	168,45
Mayagüez	560	6,440	257,600	81,144	413,834,400	168,45
Risaralda	280	3,220	128,800	40,572	206,917,200	84.23

The population in Colombia in 2022 was 51,609,000 and the per capita consumption of electricity in Colombia was 1,568.3 kWh, so the electricity generated in scenarios 1, 2, 3 and 4 could supply 0.31%, 0.39%, 0.46% and 0.54% respectively of the electricity consumption demand in Colombia. In a study conducted by Melo et al. (48) the electrical potential of biogas-derived vinasse in the state of São Paulo was analyzed, estimating a production of 9,928 GWh/year in a conservative scenario and 15,675 GWh/year in an optimized scenario. This represents approximately 0.0064% and 0.0101% of the installed electricity generation potential in the state, respectively. Marcucci et al. (49) estimated that vinasse digestion and co-digestion in the state of Paraná could generate between 36,695 and 47,245 MWh/year, which represents between 0.1% and 0.13% of the state's electricity consumption.

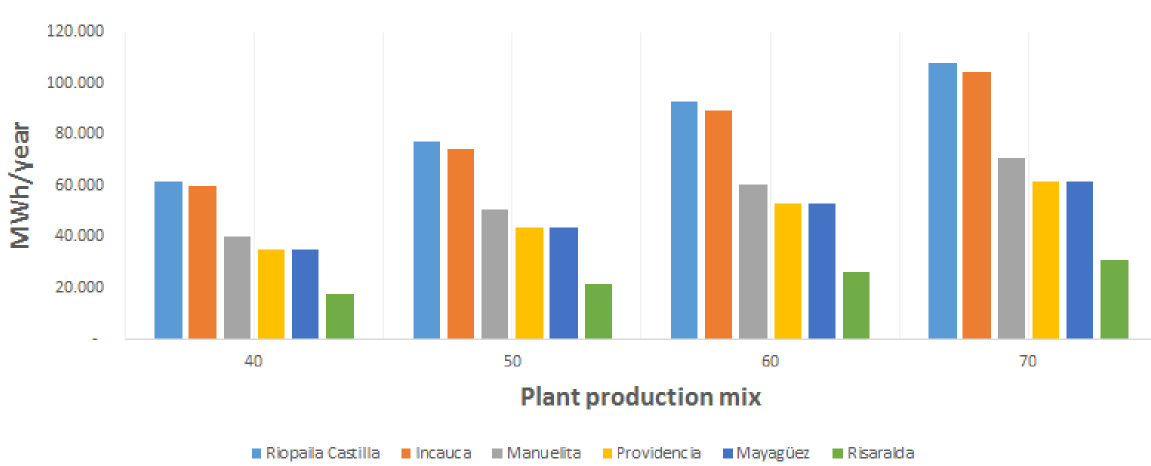

Figure 1. Production of electrical energy for different scenarios

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Table 6. Avoided GHG emissions for the scenarios studied.

Parameters	Units	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Avoided GHG electricity	Ton CO_2/ year	31,475.26	39,344.07	47,212.89	55,081.70

By 2030, Colombia has committed to reduce its greenhouse gas (GHG) emissions by 51% as part of the Paris Agreement which means that Colombia aims to emit a maximum of 169.4 million tonnes of carbon dioxide by that year, and by 2050 is expected to reach carbon neutrality by 2050. The results of the study show that the carbon dioxide emissions avoided for the scenarios studied vary between 31,475.26 and 55,081.70 tonnes of carbon dioxide per year, equivalent to 0.018 and 0.031% of the target proposed by the Colombian government. Bernal et al. (50) evaluated the economic feasibility, energy potential, and avoided CO_2 emissions associated with the combustion of biogas produced from vinasse in Brazil. The results showed that generating electricity from vinasse biogas could avoid more than 2.12% of the national industry's CO_2 emissions.

Conclusions

The potential for electricity generation from biogas derived from the biodigestion of sugar cane vinasse is a renewable energy source, which reduces the pressure on non-renewable sources. The electricity produced in scenario 4 (when 70% of the sugar cane juice will be used for ethanol production) is 437,156.37 MWh/year which could substitute 0.54% of the electricity demand in Colombia. The GHG emissions avoided with the implementation of anaerobic digestion for the treatment of vinasse and subsequent electricity production represent between 0.018 and 0.031% of the target proposed by the Colombian government to reduce GHG emissions. Future work may focus on evaluating economic targets and/or evaluating other feedstocks for electricity production.

CrediT authorship contribution statement

Conceptualization - Ideas: Jorge Eduardo Infante Cuan, Sergio Daniel Martínez Campo, Patricia Milena Muñoz Prada. Data Curation: Jorge Eduardo Infante Cuan, María Margarita, Rosa Sierra Carrillo. Formal analysis: Jorge Eduardo Infante Cuan, Sergio Daniel Martínez Campo. Investigation: Jorge Eduardo Infante Cuan, Leandro Raúl Rozo Martínez. Methodology: Jorge Eduardo Infante Cuan, Sergio Daniel Martínez Campo, María Margarita Rosa Sierra Carrillo. Project Management: Jorge Eduardo Infante Cuan, Sergio Daniel Martínez Campo. Resources: Jorge Eduardo Infante Cuan, Sergio Daniel Martínez Campo. Software: Jorge Eduardo Infante Cuan, Leandro Raúl Rozo Martínez Supervision: Jorge Eduardo Infante Cuan, Sergio Daniel Martínez Campo. Validation: Jorge Eduardo Infante Cuan, Maria Margarita Rosa Sierra Carrillo, Patricia Milena Muñoz Prada. Visualisation: Jorge Eduardo Infante Cuan. Writing - original draft - Preparation: Jorge Eduardo Infante Cuan, Leandro Raúl Rozo Martínez, Patricia Milena Muñoz Prada. Writing - revision and editing - Preparation: Jorge Eduardo Infante Cuan, Sergio Daniel Martínez Campo, Maria Margarita Rosa Sierra Carrillo, Leandro Raúl Rozo Martínez, Patricia Milena Muñoz Prada.

Financing: does not declare. Conflict of interest: does not declare. Ethical aspect: does not declare.

doi: 10.25100/iyc.v27i2.14813

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